Theoretical research of helium pulsating heat pipe under steady state

C1PoJ-05

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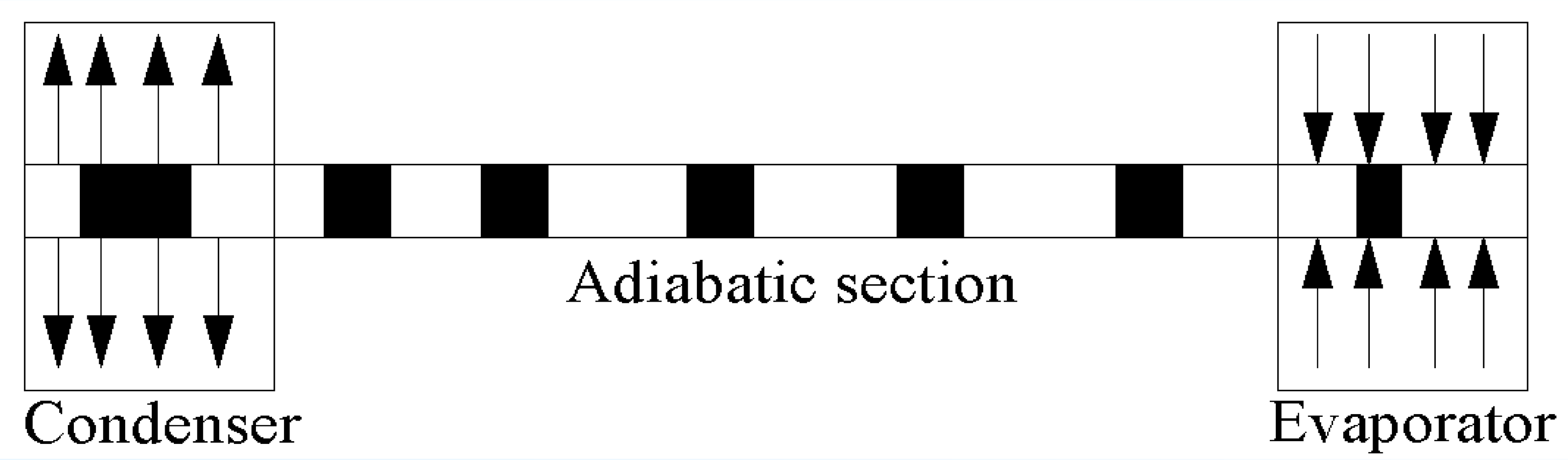
Introduction

As a new-type heat pipe, pulsating heat pipe (PHP) has several outstanding features, such as great heat transport ability, strong adjustability, small size and simple construction. PHP is a complex two-phase flow system associated with many physical subjects and parameters, which utilizes the pressure and temperature changes in volume expansion and contraction during phase changes to excite the pulsation motion of liquid plugs and vapor bubbles in the capillary tube between the evaporator and the condenser. At present time, some experimental investigation of helium PHP have been done. However, theoretical research of helium PHP is rare. In this paper, the physical and mathematical models of operating mechanism for helium PHP under steady state are established based on the conservation of mass, momentum, and energy. Several important parameters are correlated and solved, including the liquid filling ratio, flow velocity, heat power, temperature and etc. Based on the results, the operational driving force and flow resistances of helium PHP are analyzed, and the flow and heat transfer is further studied.

Physical model

The physical model which consists of a tube with a condenser, an evaporator and an adiabatic section filled with both the liquid and vapor phases is established.



The model is developed on the following assumptions and simplifications:

(1) Without regard for the transient state in the condenser and evaporator, the liquid helium and helium gas in the tube could be considered under steady state condition, which means the speed of helium plugs is constant.

(2) The liquid helium and helium gas in the tube is under saturation state condition, and the gas could be described by the state equation of ideal gas.

Mathematical model

Mathematical modelling of helium pulsating heat pipe involves many processes, including phase changes, capillary force, wall shear stress, gravity and so on, which is coupled with fundamental laws of the conservation of mass, momentum and energy.

Conservation of mass

$$\phi_0\rho_l AV + \Delta\dot{m}_{l,e} = \phi_1\rho_l AV$$

$$\phi_1\rho_l AV + \Delta\dot{m}_{l,c} = \phi_0\rho_l AV$$

$$(1-\phi_0)\rho_{v,e}AV + \Delta\dot{m}_{v,e} = (1-\phi_1)\rho'_{v,e}AV$$

$$(1-\phi_1)\rho_{v,c}AV + \Delta\dot{m}_{v,c} = (1-\phi_0)\rho'_{v,c}AV$$

Conservation of momentum

$$\Delta P_q = \Delta P_f + \Delta P_c + \Delta P_g$$

$$\Delta P_q = \rho'_{v,e}RT_h - \rho'_{v,c}RT_c$$

$$\Delta P_f = \frac{32LV}{d^2}[\mu_l\frac{\phi_0+\phi_1}{2} + \mu_v(1-\frac{\phi_0+\phi_1}{2})]$$

$$\Delta P_c = \pi d\sigma(\cos\theta_{rec} - \cos\theta_{adv})$$

$$\Delta P_g = \pm\rho_l gL\sin\alpha$$

Conservation of energy

$$\Delta\dot{m}_{v,e} = -\Delta\dot{m}_{l,e} = \frac{\beta Q}{r}$$

$$\Delta\dot{m}_{l,c} = -\Delta\dot{m}_{v,c} = \frac{Q_c}{r}$$

$$\phi_1 = \phi_0 - \frac{\beta Q}{\rho_l AVr}$$

$$\delta = 1.16[\frac{\mu_l d\lambda_l(T_h - T_c)}{g\sin\alpha r\rho_l^2}]^{0.25}$$

$$Q_c = \pi(d-2\delta)\lambda_l(\frac{T_h+T_c}{2} - T_c)\frac{L_c[1-(\phi_0+\phi_1)/2]}{\delta}$$

$$(1-\beta)Q = \frac{\phi_0+\phi_1}{2}\rho_l AVc_p(T_h - T_c)$$

By trying to incorporate the constitutive relationships, the equations above have merged into three equations with three variable (Q_c,β, and V)and could be solved by using the method of least square.

Results and discuss

For helium pulsating heat pipe, the proportion of the latent heat transfer to the total heat transfer in the evaporator β represents the heat transfer characteristics and the velocity of plugs V represents the flow characteristics

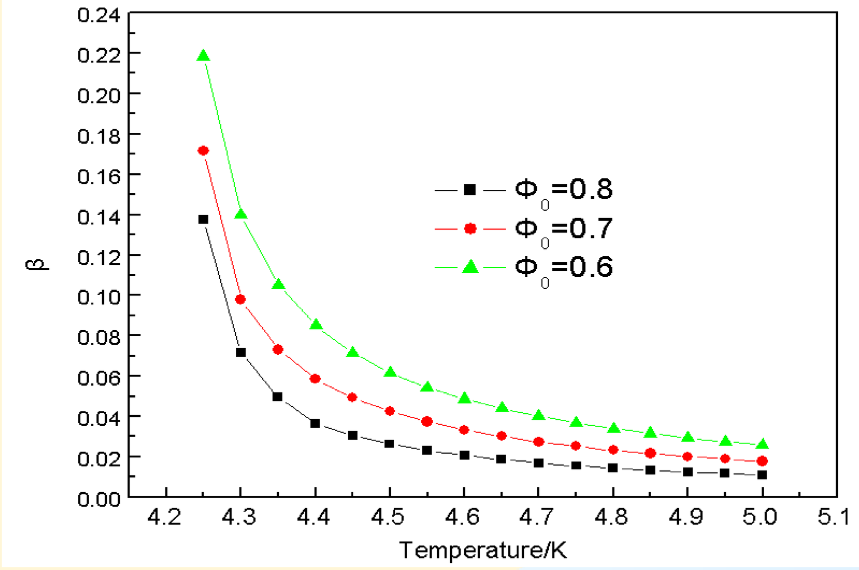


Fig.1

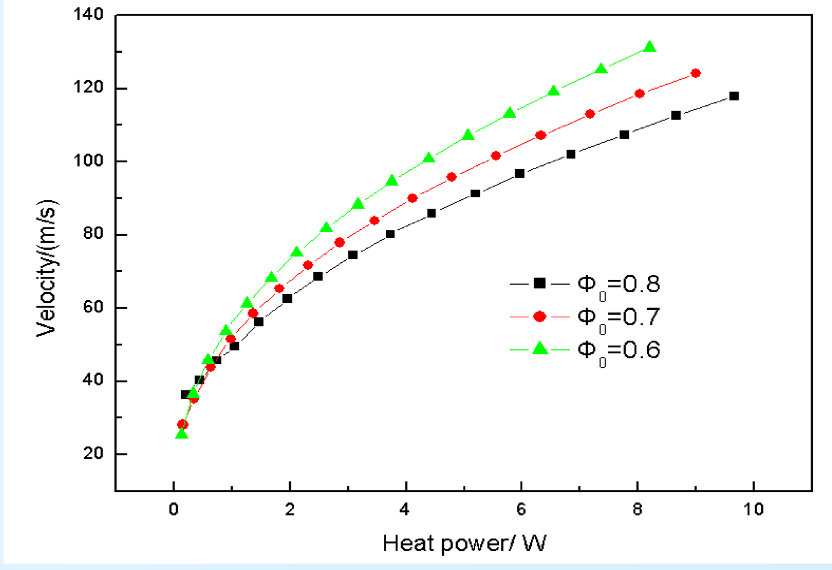


Fig.2

Fig.1: the proportion β as a function of temperature with a parameter of liquid filling ratio.

Fig.2:velocity as a function of heat power with a parameter of liquid filling ratio

- The proportion β is low (1%~20%), which means most of the heat transfers through the helium pulsating heat pipe is in the form of sensible heat transfer. Moreover, with the increase of the temperature of the evaporator, the proportion decreases, and the sensible heat is playing an ever-growing role in the heat transfer process. However, the sensible heat transfer depends on the difference in temperature. That is the reason why the temperature of the evaporator rapidly rises along with the increase of the heat power. With the increase of liquid filling ratio, the area of phase transformation decreases. Therefore, the phase change heat transfer decreases, and the proportion of the latent heat transfer to the total heat transfer in the evaporator decreases.
- The velocity V increases when increasing the heat power. That is because the increased heat power results in the increase of temperature difference and then elevates the driving force. As is known, the smaller the liquid filling ratio is, the less the flow resistance is. Therefore, the velocity will increase with the decrease of the liquid filling ratio.